

TITLE OF THE INVENTION

GAMMA-CONOPEPTIDES

CROSS-REFERENCE TO RELATED APPLICATION

- 5 D The present application ^{claims benefit} ~~is related~~ to U.S. provisional patent application Serial No. 60/069,706, filed 16 December 1997, incorporated herein by reference.

10 This invention was made in part with Government support under Grant No. RR01614 and GM48677 awarded by the National Institutes of Health, Bethesda, Maryland and under Grant No. DIR8700766 awarded by the National Science Foundation, Washington, D.C. The United States Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

20 This invention relates to relatively short peptides about 25-40 residues in length, which are naturally available in minute amounts in the venom of the cone snails or analogs to the naturally available peptides, and which include three cyclizing disulfide linkages and one or more γ -carboxyglutamate residues.

25 The publications and other materials used herein to illuminate the background of the invention, and in particular, cases to provide additional details respecting the practice, are incorporated by reference, and for convenience are referenced in the following text by author and date and are listed alphabetically by author in the appended bibliography.

30 Mollusks of the genus *Conus* produce a venom that enables them to carry out their unique predatory lifestyle. Prey are immobilized by the venom that is injected by means of a highly specialized venom apparatus, a disposable hollow tooth that functions both in the manner of a harpoon and a hypodermic needle.

Few interactions between organisms are more striking than those between a venomous animal and its envenomated victim. Venom may be used as a primary weapon to capture prey or as a defense mechanism. Many of these venoms contain molecules directed to receptors and ion channels of neuromuscular systems.

35 The predatory cone snails (*Conus*) have developed a unique biological strategy. Their venom contains relatively small peptides that are targeted to various neuromuscular receptors and may be equivalent in their pharmacological diversity to the alkaloids of plants or secondary metabolites of microorganisms. Many of these peptides are among the smallest nucleic acid-

encoded translation products having defined conformations, and as such, they are somewhat unusual. Peptides in this size range normally equilibrate among many conformations. Proteins having a fixed conformation are generally much larger.

5 The cone snails that produce these toxic peptides, which are generally referred to as conotoxins or conotoxin peptides, are a large genus of venomous gastropods comprising approximately 500 species. All cone snail species are predators that inject venom to capture prey, and the spectrum of animals that the genus as a whole can envenomate is broad. A wide variety of hunting strategies are used, however, every *Conus* species uses fundamentally the same basic pattern of envenomation.

10 Several peptides isolated from *Conus* venoms have been characterized. These include the α -, μ - and ω -conotoxins which target nicotinic acetylcholine receptors, muscle sodium channels, and neuronal calcium channels, respectively (Olivera et al., 1985). A conotoxin, TxVIIA, containing a γ -carboxyglutamate residue and three disulfide bonds has been isolated (Fainzilber et al., 1991). Conopressins, which are vasopressin analogs, have also been identified (Cruz et al., 1987). In addition, peptides named conantokins have been isolated from *Conus geographus* and *Conus tulipa* (Mena et al., 1990; Haack et al., 1990). These peptides have unusual age-dependent physiological effects: they induce a sleep-like state in mice younger than two weeks and hyperactive behavior in mice older than 3 weeks (Haack et al., 1990). Recently, peptides named contryphans containing D-tryptophan or D-leucine residues have been isolated from *Conus radiatus* (U.S. Serial No. 09/061,026), and bromo-tryptophan conopeptides have been isolated from *Conus imperialis* and *Conus radiatus* (U.S. Serial No. 08/785,534).

25 Ion channels are integral plasma membrane proteins responsible for electrical activity in excitable tissues. It has been recognized that slow inward currents can influence neuronal excitability via long-lasting depolarizations of the cell membrane (Llinás, 1988). The role of slow inward currents in generating endogenous bursting behavior has been recognized in molluscan neurons (Wilson & Wachtel, 1974; Eckert & Lux, 1976; Partridge et al., 1979), and more recently in some types of mammalian neurons (Lanthorn et al., 1984; Stafstrom et al., 1985; Llinás, 1988; Alonso & Llinás, 1989). Changes in the slow inward currents carried by such nonspecific cation channels may play a crucial role in bursting and pacemaker activities in a variety of excitable systems, ranging from mammalian heart muscle to molluscan neurons (Partridge & Swandulla, 30 1988; Hoehn et al., 1993; Kits & Mansvelder, 1966; van Soest & Kits, 1997). Slow inward currents

INS B2 are also believed to be important in generating epileptiform bursting in regions of the brain such as the hippocampus.

It is desired to identify drugs which are useful for modulating slow inward cation channels in vertebrates involved in syndromes of clinical relevance, such as epileptic activity in hippocampus
5 (Hoehn et al., 1993) and pacemaker potentials in heart muscle (Reuter, 1984).

SUMMARY OF THE INVENTION

This invention relates to relatively short peptides about 25-40 residues in length, which are naturally available in minute amounts in the venom of the cone snails or analogs to the naturally
10 available peptides, and which include three cyclizing disulfide linkages and one or more γ -carboxyglutamate residues.

More specifically, the present invention is directed to conopeptides having the general formula I:

Xaa₁-Cys-Xaa₂-Cys-Xaa₃-Xaa₄-Cys-Cys-Xaa₅-Cys-Xaa₆-Cys-Xaa₇ (SEQ ID NO:1), wherein Xaa₁ is des-Xaa₁ or a peptide having 1-6 amino acids; Xaa₂ is a peptide having 5-6 amino acids; Xaa₃ is a peptide having 4 amino acids; Xaa₄ is Glu, γ -Glu (γ -carboxyglutamic acid; also referred to as Gla) or Gln; Xaa₅ is a peptide having 3-4 amino acids; Xaa₆ is a peptide having 3-6 amino acids; and Xaa₇ is des-Xaa₇ or a peptide having 2-9 amino acids, with the proviso that when Xaa₁ is des-Xaa₁, then Xaa₅ is not the tripeptide Ser-Asp-Asn;
20

general formula II:

Xaa₁-Cys-Xaa₂-Cys-Xaa₃-Xaa₄-Cys-Cys-Xaa₅-Xaa₆-Cys-Xaa₇-Cys-Xaa₈ (SEQ ID NO:2), wherein Xaa₁ is des-Xaa₁ or a peptide having 1-6 amino acids; Xaa₂ is a peptide having 5-6 amino acids; Xaa₃ is a peptide having 4 amino acids; Xaa₄ is Glu, γ -Glu or Gln; Xaa₅ is Ser or Thr; Xaa₆ is a peptide having 2-3 amino acids; Xaa₇ is a peptide having 3-6 amino acids; and Xaa₈ is des-Xaa₈ or a peptide having 2-9 amino acids, with the proviso that when Xaa₁ is des-Xaa₁ and Xaa₅ is Ser, then Xaa₆ is not the dipeptide Asp-Asn;
25

general formula III:

Xaa₁-Cys-Xaa₂-Cys-Xaa₃-Xaa₄-Cys-Cys-Ser-Asn-Ser-Cys-Asp-Xaa₅-Cys-Xaa₆ (SEQ ID NO:3), wherein Xaa₁ is a peptide having 1-6 amino acids; Xaa₂ is a
30

hexapeptide; Xaa₃ is a peptide having 4 amino acids; Xaa₄ is Glu or γ -Glu; Xaa₅ is a tripeptide; and Xaa₆ is a peptide having 7-9 amino acids;

general formula IV:

Xaa₁-Cys-Xaa₂-Cys-Xaa₃-Xaa₄-Xaa₅-Cys-Cys-Ser-Asn-Ser-Cys-Asp-Xaa₆-Cys-Xaa₇ (SEQ ID NO:4), wherein Xaa₁ is a peptide having 1-6 amino acids; Xaa₂ is a hexapeptide; Xaa₃ is Ser or Thr; Xaa₄ is a tripeptide; Xaa₅ is Glu or γ -Glu; Xaa₆ is a tripeptide; and Xaa₇ is a peptide having 7-9 amino acids;

or general formula V:

Xaa₁-Xaa₂-Cys-Xaa₃-Xaa₄-Phe-Xaa₅-Cys-Thr-Xaa₆-Ser-Xaa₇-Cys-Cys-Ser-Asn-Ser-Cys-Asp-Gln-Thr-Tyr-Cys-Xaa₈-Leu-Xaa₉ (SEQ ID NO:5), wherein Xaa₁ is des-Xaa₁ or a dipeptide; Xaa₂ is Asp, Glu or γ -Glu; Xaa₃ is a dipeptide; Xaa₄ is Trp or 6-bromo-Trp; Xaa₅ is a dipeptide; Xaa₆ is a dipeptide; Xaa₇ is Glu or γ -Glu; Xaa₈ is any amino acid; and, Xaa₉ is a pentapeptide.

The amino acid or the amino acid residues of the peptides is an amino acid selected from the group consisting of natural, modified or non-natural amino acids. The disulfide bridges in the conopeptides of general formulas I-V (as well as the specific conopeptides described herein) are between the first and fourth cysteine residues, between the second and fifth cysteine residues and between the third and sixth cysteine residues. The C-terminal end may contain a carboxyl or amide group. The invention also includes pharmaceutically acceptable salts of the conopeptides. These conopeptides are useful for modulating slow inward cation channels in vertebrates involved in syndromes of clinical relevance, such as epileptic activity in hippocampus (Hoehn et al., 1993) and pacemaker potentials in heart muscle (Reuter, 1984). Thus, the conopeptides are useful as agonists of neuronal pacemaker cation channels.

The invention further relates to the specific peptides:

Asp-Cys-Thr-Ser-Xaa₁-Phe-Gly-Arg-Cys-Thr-Val-Asn-Ser-Xaa₂-Cys-Cys-Ser-Asn-Ser-Cys-Asp-Gln-Thr-Tyr-Cys-Xaa₂-Leu-Tyr-Ala-Phe-Xaa₃-Ser (SEQ ID NO:6) (PnVIIA), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ -Glu, preferably γ -Glu; Xaa₃ is Pro or hydroxy-Pro (Hyp), preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably a free carboxyl group;

Xaa₁-Leu-Xaa₂-Cys-Ser-Val-Xaa₁-Phe-Ser-His-Cys-Thr-Lys-Asp-Ser-Xaa₂-Cys-Cys-Ser-Asn-Ser-Cys-Asp-Gln-Thr-Tyr-Cys-Thr-Leu-Met-Xaa₃-Xaa₃-Asp-Xaa₁ (SEQ ID NO:7) (Tx6.4), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ-Glu, preferably γ-Glu; Xaa₃ is Pro or Hyp, preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably a free carboxyl group;

Xaa₁-Xaa₁-Arg-Xaa₁-Gly-Gly-Cys-Met-Ala-Xaa₁-Phe-Gly-Leu-Cys-Ser-Arg-Asp-Ser-Xaa₂-Cys-Cys-Ser-Asn-Ser-Cys-Asp-Val-Thr-Arg-Cys-Xaa₂-Leu-Met-Xaa₃-Phe-Xaa₃-Xaa₃-Asp-Xaa₁ (SEQ ID NO:8) (Tx6.9), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ-Glu, preferably γ-Glu; Xaa₃ is Pro or Hyp, preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably a free carboxyl group;

Cys-Lys-Thr-Tyr-Ser-Lys-Tyr-Cys-Xaa₂-Ala-Asp-Ser-Xaa₂-Cys-Cys-Thr-Xaa₂-Gln-Cys-Val-Arg-Ser-Tyr-Cys-Thr-Leu-Phe (SEQ ID NO:9) (J010), wherein Xaa₂ is Glu or γ-Glu, preferably γ-Glu; and the C-terminus is a free carboxyl group or is amidated, preferably amidated;

Asp-Xaa₁-Xaa₁-Asp-Asp-Gly-Cys-Ser-Val-Xaa₁-Gly-Xaa₃-Cys-Thr-Val-Asn-Ala-Xaa₂-Cys-Cys-Ser-Gly-Asp-Cys-His-Xaa₂-Thr-Cys-Ile-Phe-Gly-Xaa₁-Xaa₂-Val (SEQ ID NO:10) (Tx6.6), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ-Glu, preferably γ-Glu; Xaa₃ is Pro or Hyp, preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably a free carboxyl group;

Gly-Met-Xaa₁-Gly-Xaa₂-Cys-Lys-Asp-Gly-Leu-Thr-Thr-Cys-Leu-Ala-Xaa₃-Ser-Xaa₂-Cys-Cys-Ser-Xaa₂-Asp-Cys-Xaa₂-Gly-Ser-Cys-Thr-Met-Xaa₁ (SEQ ID NO:11) (Tx6.5), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ-Glu, preferably γ-Glu; Xaa₃ is Pro or Hyp, preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably a free carboxyl group;

Xaa₂-Cys-Arg-Ala-Xaa₁-Tyr-Ala-Xaa₃-Cys-Ser-Xaa₃-Gly-Ala-Gln-Cys-Cys-Ser-Leu-Leu-Met-Cys-Ser-Lys-Ala-Thr-Ser-Arg-Cys-Ile-Leu-Ala-Leu (SEQ ID NO:12) (Gm6.7), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ-Glu, preferably γ-Glu; Xaa₃ is Pro or Hyp, preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably a free carboxyl group;

Asn-Gly-Gln-Cys-Xaa₂-Asp-Val-Xaa₁-Met-Xaa₃-Cys-Thr-Ser-Asn-Xaa₁-Xaa₂-Cys-Cys-Ser-Leu-Asp-Cys-Xaa₂-Met-Tyr-Cys-Thr-Gln-Ile (SEQ ID NO:13)

(Mr6.1), wherein Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ -Glu, preferably γ -Glu; Xaa₃ is Pro or Hyp, preferably Hyp; and the C-terminus is a free carboxyl group or is amidated, preferably amidated;

Cys-Gly-Gly-Xaa₁-Ser-Thr-Tyr-Cys-Xaa₂-Val-Asp-Xaa₂-Xaa₂-Cys-Cys-Ser-
Xaa₂-Ser-Cys-Val-Arg-Ser-Tyr-Cys-Thr-Leu-Phe (SEQ ID NO:14) (Mr6.2), wherein
Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ -Glu, preferably γ -Glu; and the C-
terminus is a free carboxyl group or is amidated, preferably amidated;

Asn-Gly-Gly-Cys-Lys-Ala-Thr-Xaa₁-Met-Ser-Cys-Ser-Ser-Gly-Xaa₁-Xaa₂.
Cys-Cys-Ser-Met-Ser-Cys-Asp-Met-Try-Cys (SEQ ID NO:15) (Mr6.3), wherein
Xaa₁ is Trp or 6-bromo-Trp; Xaa₂ is Glu or γ -Glu, preferably γ -Glu; and the C-
terminus is a free carboxyl group or is amidated, preferably amidated.

Finally, the invention further relates to the propeptide sequences for the above peptides and the DNA sequences coding for these propeptide sequences as described in further detail herein.

SEQUENCE SUMMARY

SEQ ID NO:1 = γ -conopeptides of general formula I; SEQ ID NO:2 = γ -conopeptides of general formula II; SEQ ID NO:3 = γ -conopeptides of general formula III; SEQ ID NO:4 = γ -conopeptides of general formula IV; SEQ ID NO:5 = γ -conopeptides of general formula V; SEQ ID NO:6 = γ -conopeptide corresponding to PnVIIA; SEQ ID NO:7 = γ -conopeptide corresponding to Tx6.4; SEQ ID NO:8 = γ -conopeptide corresponding to Tx6.9; SEQ ID NO:9 = γ -conopeptide corresponding to J010; SEQ ID NO:10 = γ -conopeptide corresponding to Tx6.6; SEQ ID NO:11 = γ -conopeptide corresponding to Tx6.5; SEQ ID NO:12 = γ -conopeptide corresponding to Gm6.7; SEQ ID NO:13 = γ -conopeptide corresponding to Mr6.1; SEQ ID NO:14 = γ -conopeptide corresponding to Mr6.2; SEQ ID NO:15 = γ -conopeptide corresponding to Mr6.3; SEQ ID NO:16 = DNA encoding propeptide of Tx6.4; SEQ ID NO:17 = propeptide of Tx6.4; SEQ ID NO:18 = DNA encoding propeptide of Tx6.9; SEQ ID NO:19 = propeptide of Tx6.9; SEQ ID NO:20 = DNA encoding propeptide of J010; SEQ ID NO:21 = propeptide of J010; SEQ ID NO:22 = DNA encoding propeptide of Tx6.6; SEQ ID NO:23 = propeptide of Tx6.6; SEQ ID NO:24 = DNA encoding propeptide of Tx6.5; SEQ ID NO:25 = propeptide of Tx6.5; SEQ ID NO:26 = DNA encoding propeptide of Gm6.7; SEQ ID NO:27 = propeptide of Gm6.7; SEQ ID NO:28 = DNA encoding propeptide of Mr6.1; SEQ ID NO:29 = propeptide of Mr6.1; SEQ ID NO:30 = DNA encoding

propeptide of Mr6.2; SEQ ID NO:31 = propeptide of Mr6.2; SEQ ID NO:32 = DNA encoding propeptide of Mr6.3; SEQ ID NO:33 = propeptide of Mr6.3; SEQ ID NO:34 = DNA encoding propeptide of Tx6.1; SEQ ID NO:35 = propeptide of Tx6.1; SEQ ID NO:36 = γ -conopeptide corresponding to Tx6.1; SEQ ID NO:37 = consensus sequence of γ -conopeptides PnVIIA and Tx6.4; SEQ ID NO:38 = degenerate probe for consensus sequence of γ -conopeptides; SEQ ID NO:39 = degenerate probe for consensus sequence of γ -conopeptides; SEQ ID NO:40 = consensus sequence of pro- γ -conopeptides; SEQ ID NO:41 = degenerate probe for consensus sequence of pro- γ -conopeptides; SEQ ID NO:42 = γ -conopeptide PnVIIA; SEQ ID NO:43 = γ -conopeptide TxVIIA; SEQ ID NO:44 = N-terminal tryptic peptide of γ -conopeptide PnVIIA; SEQ ID NO:45 = C-terminal tryptic peptide of γ -conopeptide PnVIIA; SEQ ID NO:46 = primer for isolating conopeptides from *Conus textile* cDNA library; SEQ ID NO:47 = primer for isolating conopeptides from *Conus textile* cDNA library.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

This invention relates to relatively short peptides about 25-40 residues in length, which are naturally available in minute amounts in the venom of the cone snails or analogs to the naturally available peptides, and which include three cyclizing disulfide linkages and one or more γ -carboxyglutamate residues.

More specifically, the present invention is directed to conopeptides having the general formulas I-V described above. The invention is also directed to the specific γ -conopeptides PnVIIA, Tx6.4, Tx6.9, J010, Tx6.6, Tx6.5, Gm6.7, Mr6.1, Mr6.2 and Mr6.3, the sequences of which are described above.

The invention is further directed to isolated nucleic acids which encode γ -conopeptides, including the above and γ -conopeptide Tx6.1, and to isolated propeptides encoded by the nucleic acids. This aspect of the present invention is set forth in Table 1.

TABLE 1

Nucleic Acids and Propeptides of γ -Conopeptides

γ -Conopeptide	Nucleic Acid SEQ ID NO:	Propeptide SEQ ID NO:
Tx6.4	16	17
Tx6.9	18	19
J010	20	21
Tx6.6	22	23
Tx6.5	24	25
Gm6.7	26	27
Mr6.1	28	29
Mr6.2	30	31
Mr6.3	32	33
Tx6.1	34	35

The mature peptide sequence for Tx6.1 is LCX₃DYTX₂X₃CSHAHX₂CCSX₁NCYNGHCT (SEQ ID NO:36), wherein X₁, X₂ and X₃ are as described for Xaa₁, Xaa₂ and Xaa₃ respectively. The C-terminus is preferably amidated.

The conopeptides of the present invention are useful for modulating slow inward cation channels in vertebrates involved in syndromes of clinical relevance, such as epileptic activity in hippocampus (Hoehn et al., 1993) and pacemaker potentials in heart muscle (Reuter, 1984). Thus, the conopeptides are useful as agonists of neuronal pacemaker cation channels.

The γ -conopeptides of the present invention are identified by isolation from *Conus* venom. Alternatively, the γ -conopeptides of the present invention are identified using recombinant DNA techniques. According to this method of identification, cDNA libraries of various *Conus* species are screened using conventional techniques with degenerate probes for the peptide consensus sequence Xaa-Cys-Cys-Ser (SEQ ID NO:37), wherein Xaa is Glu or Gln. Suitable probes are 5' SARTGYTGYAGY 3' (SEQ ID NO:38) or 5' SARTGYTGYTCN 3' (SEQ ID NO:39). Alternatively, cDNA libraries are screened with degenerate probes for the propeptide consensus sequence Ile-Leu-Leu-Val-Ala-Ala-Val-Leu (SEQ ID NO:40). Suitable probes for this sequence are 5' ATHYTNYTNGTNGCNGCNGTNYTN 3' (SEQ ID NO:41). Clones which hybridize to these probes are analyzed to identify those which meet minimal size requirements, i.e., clones having approximately 300 nucleotides (for a propeptide), as determined using PCR primers which flank the cDNA cloning sites for the specific cDNA library being examined. These minimal-sized clones are then sequenced. The sequences are then examined for the presence of a peptide having the characteristics noted above for γ -conopeptides, such as the presence of a Glu residue which could

be modified to a γ -Glu and 6 cysteine residues. The biological activity of the peptides identified by this method is tested as described herein.

These peptides are sufficiently small to be chemically synthesized. General chemical syntheses for preparing the foregoing conopeptides peptides are described hereinafter, along with specific chemical synthesis of conopeptides and indications of biological activities of these synthetic products. Various ones of these conopeptides can also be obtained by isolation and purification from specific *Conus* species using the techniques described in U.S. Patent Nos. 4,447,356 (Olivera et al., 1984), 5,514,774 (Olivera et al., 1996) and 5,591,821 (Olivera et al., 1997), the disclosures of which are incorporated herein by reference.

Although the conopeptides of the present invention can be obtained by purification from cone snails, because the amounts of conopeptides obtainable from individual snails are very small, the desired substantially pure conopeptides are best practically obtained in commercially valuable amounts by chemical synthesis using solid-phase strategy. For example, the yield from a single cone snail may be about 10 micrograms or less of conopeptide. By "substantially pure" is meant that the peptide is present in the substantial absence of other biological molecules of the same type; it is preferably present in an amount of at least about 85% purity and preferably at least about 95% purity. Chemical synthesis of biologically active conopeptides depends of course upon correct determination of the amino acid sequence. Thus, the conopeptides of the present invention may be isolated, synthesized and/or substantially pure.

The conopeptides can also be produced by recombinant DNA techniques well known in the art. Such techniques are described by Sambrook et al. (1979). The peptides produced in this manner are isolated, reduced if necessary, and oxidized to form the correct disulfide bonds, if present in the final molecule.

One method of forming disulfide bonds in the conopeptides of the present invention is the air oxidation of the linear peptides for prolonged periods under cold room temperatures or at room temperature. This procedure results in the creation of a substantial amount of the bioactive, disulfide-linked peptides. The oxidized peptides are fractionated using reverse-phase high performance liquid chromatography (HPLC) or the like, to separate peptides having different linked configurations. Thereafter, either by comparing these fractions with the elution of the native material or by using a simple assay, the particular fraction having the correct linkage for maximum biological potency is easily determined. It is also found that the linear peptide, or the oxidized product having more than one fraction, can sometimes be used for *in vivo* administration because the cross-linking

and/or rearrangement which occurs *in vivo* has been found to create the biologically potent conopeptide molecule. However, because of the dilution resulting from the presence of other fractions of less biopotency, a somewhat higher dosage may be required.

The peptides are synthesized by a suitable method, such as by exclusively solid-phase techniques, by partial solid-phase techniques, by fragment condensation or by classical solution couplings.

In conventional solution phase peptide synthesis, the peptide chain can be prepared by a series of coupling reactions in which constituent amino acids are added to the growing peptide chain in the desired sequence. Use of various coupling reagents, e.g., dicyclohexylcarbodiimide or diisopropylcarbonyldimidazole, various active esters, e.g., esters of N-hydroxyphthalimide or N-hydroxy-succinimide, and the various cleavage reagents, to carry out reaction in solution, with subsequent isolation and purification of intermediates, is well known classical peptide methodology. Classical solution synthesis is described in detail in the treatise, "Methoden der Organischen Chemie (Houben-Weyl): Synthese von Peptiden," (1974). Techniques of exclusively solid-phase synthesis are set forth in the textbook, "Solid-Phase Peptide Synthesis," (Stewart and Young, 1969), and are exemplified by the disclosure of U.S. Patent 4,105,603 (Vale et al., 1978). The fragment condensation method of synthesis is exemplified in U.S. Patent 3,972,859 (1976). Other available syntheses are exemplified by U.S. Patents No. 3,842,067 (1974) and 3,862,925 (1975). The synthesis of peptides containing γ -carboxyglutamic acid residues is exemplified by Rivier et al. (1987), Nishiuchi et al. (1993) and Zhou et al. (1996). Synthesis of conopeptides have been described in U.S. Patent Nos. 4,447,356 (Olivera et al., 1984), 5,514,774 (Olivera et al., 1996) and 5,591,821 (Olivera et al., 1997).

Common to such chemical syntheses is the protection of the labile side chain groups of the various amino acid moieties with suitable protecting groups which will prevent a chemical reaction from occurring at that site until the group is ultimately removed. Usually also common is the protection of an α -amino group on an amino acid or a fragment while that entity reacts at the carboxyl group, followed by the selective removal of the α -amino protecting group to allow subsequent reaction to take place at that location. Accordingly, it is common that, as a step in such a synthesis, an intermediate compound is produced which includes each of the amino acid residues located in its desired sequence in the peptide chain with appropriate side-chain protecting groups linked to various ones of the residues having labile side chains.

As far as the selection of a side chain amino protecting group is concerned, generally one is chosen which is not removed during deprotection of the α -amino groups during the synthesis. However, for some amino acids, e.g., His, protection is not generally necessary. In selecting a particular side chain protecting group to be used in the synthesis of the peptides, the following general rules are followed: (a) the protecting group preferably retains its protecting properties and is not split off under coupling conditions, (b) the protecting group should be stable under the reaction conditions selected for removing the α -amino protecting group at each step of the synthesis, and (c) the side chain protecting group must be removable, upon the completion of the synthesis containing the desired amino acid sequence, under reaction conditions that will not undesirably alter the peptide chain.

It should be possible to prepare many, or even all, of these peptides using recombinant DNA technology. However, when peptides are not so prepared, they are preferably prepared using the Merrifield solid-phase synthesis, although other equivalent chemical syntheses known in the art can also be used as previously mentioned. Solid-phase synthesis is commenced from the C-terminus of the peptide by coupling a protected α -amino acid to a suitable resin. Such a starting material can be prepared by attaching an α -amino-protected amino acid by an ester linkage to a chloromethylated resin or a hydroxymethyl resin, or by an amide bond to a benzhydrylamine (BHA) resin or paramethylbenzhydrylamine (MBHA) resin. Preparation of the hydroxymethyl resin is described by Bodansky et al. (1966). Chloromethylated resins are commercially available from Bio Rad Laboratories (Richmond, CA) and from Lab. Systems, Inc. The preparation of such a resin is described by Stewart and Young (1969). BHA and MBHA resin supports are commercially available, and are generally used when the desired polypeptide being synthesized has an unsubstituted amide at the C-terminus. Thus, solid resin supports may be any of those known in the art, such as one having the formulae $-O-CH_2$ -resin support, $-NH$ BHA resin support, or $-NH$ -MBHA resin support. When the unsubstituted amide is desired, use of a BHA or MBHA resin is preferred, because cleavage directly gives the amide. In case the N-methyl amide is desired, it can be generated from an N-methyl BHA resin. Should other substituted amides be desired, the teaching of U.S. Patent No. 4,569,967 (Kornreich et al., 1986) can be used, or should still other groups than the free acid be desired at the C-terminus, it may be preferable to synthesize the peptide using classical methods as set forth in the Houben-Weyl text (1974).

The C-terminal amino acid, protected by Boc or Fmoc and by a side-chain protecting group, if appropriate, can be first coupled to a chloromethylated resin according to the procedure set forth

in Horiki et al. (1978), using KF in DMF at about 60°C for 24 hours with stirring, when a peptide having free acid at the C-terminus is to be synthesized. Following the coupling of the BOC-protected amino acid to the resin support, the α -amino protecting group is removed, as by using trifluoroacetic acid (TFA) in methylene chloride or TFA alone. The deprotection is carried out at a temperature between about 0°C and room temperature. Other standard cleaving reagents, such as HCl in dioxane, and conditions for removal of specific α -amino protecting groups may be used as described in Schroder and Lubke (1965).

After removal of the α -amino-protecting group, the remaining α -amino- and side chain-protected amino acids are coupled step-wise in the desired order to obtain the intermediate compound defined hereinbefore, or as an alternative to adding each amino acid separately in the synthesis, some of them may be coupled to one another prior to addition to the solid phase reactor. Selection of an appropriate coupling reagent is within the skill of the art. Particularly suitable as a coupling reagent is N,N'-dicyclohexylcarbodiimide (DCC, DIC, HBTU, HATU, TBTU in the presence of HoBt or HoAt).

The activating reagents used in the solid phase synthesis of the peptides are well known in the peptide art. Examples of suitable activating reagents are carbodiimides, such as N,N'-diisopropylcarbodiimide and N-ethyl-N'-(3-dimethylaminopropyl)carbodiimide. Other activating reagents and their use in peptide coupling are described by Schroder and Lubke (1965) and Kapoor (1970).

Each protected amino acid or amino acid sequence is introduced into the solid-phase reactor in about a twofold or more excess, and the coupling may be carried out in a medium of dimethylformamide (DMF):CH₂Cl₂ (1:1) or in DMF or CH₂Cl₂ alone. In cases where intermediate coupling occurs, the coupling procedure is repeated before removal of the α -amino protecting group prior to the coupling of the next amino acid. The success of the coupling reaction at each stage of the synthesis, if performed manually, is preferably monitored by the ninhydrin reaction, as described by Kaiser et al. (1970). Coupling reactions can be performed automatically, as on a Beckman 990 automatic synthesizer, using a program such as that reported in Rivier et al. (1978).

After the desired amino acid sequence has been completed, the intermediate peptide can be removed from the resin support by treatment with a reagent, such as liquid hydrogen fluoride or TFA (if using Fmoc chemistry), which not only cleaves the peptide from the resin but also cleaves all remaining side chain protecting groups and also the α -amino protecting group at the N-terminus if it was not previously removed to obtain the peptide in the form of the free acid. If Met is present

in the sequence, the Boc protecting group is preferably first removed using trifluoroacetic acid (TFA)/ethanedithiol prior to cleaving the peptide from the resin with HF to eliminate potential S-alkylation. When using hydrogen fluoride or TFA for cleaving, one or more scavengers such as anisole, cresol, dimethyl sulfide and methylethyl sulfide are included in the reaction vessel.

5 Cyclization of the linear peptide is preferably affected, as opposed to cyclizing the peptide while a part of the peptido-resin, to create bonds between Cys residues. To effect such a disulfide cyclizing linkage, fully protected peptide can be cleaved from a hydroxymethylated resin or a chloromethylated resin support by ammonolysis, as is well known in the art, to yield the fully protected amide intermediate, which is thereafter suitably cyclized and deprotected. Alternatively, 10 deprotection, as well as cleavage of the peptide from the above resins or a benzhydrylamine (BHA) resin or a methylbenzhydrylamine (MBHA), can take place at 0°C with hydrofluoric acid (HF) or TFA, followed by oxidation as described above. A suitable method for cyclization is the method described by Cartier et al. (1996).

The present γ -conotoxins are useful for modulating slow inward cation channels in vertebrates involved in syndromes of clinical relevance, such as epileptic activity in hippocampus (Hoehn et al., 1993) and pacemaker potentials in heart muscle (Reuter, 1984). Thus, the conopeptides are useful as agonists of neuronal pacemaker cation channels.

Pharmaceutical compositions containing a compound of the present invention as the active ingredient can be prepared according to conventional pharmaceutical compounding techniques. See, for example, *Remington's Pharmaceutical Sciences*, 18th Ed. (1990, Mack Publishing Co., Easton, PA). Typically, an antagonistic amount of active ingredient will be admixed with a pharmaceutically acceptable carrier. The carrier may take a wide variety of forms depending on the form of preparation desired for administration, e.g., intravenous, oral or parenteral. The compositions may further contain antioxidizing agents, stabilizing agents, preservatives and the like.

25 For oral administration, the compounds can be formulated into solid or liquid preparations such as capsules, pills, tablets, lozenges, melts, powders, suspensions or emulsions. In preparing the compositions in oral dosage form, any of the usual pharmaceutical media may be employed, such as, for example, water, glycols, oils, alcohols, flavoring agents, preservatives, coloring agents, suspending agents, and the like in the case of oral liquid preparations (such as, for example, suspensions, elixirs and 30 solutions); or carriers such as starches, sugars, diluents, granulating agents, lubricants, binders, disintegrating agents and the like in the case of oral solid preparations (such as, for example, powders, capsules and tablets). Because of their ease in administration, tablets and capsules represent the most

advantageous oral dosage unit form, in which case solid pharmaceutical carriers are obviously employed. If desired, tablets may be sugar-coated or enteric-coated by standard techniques. The active agent can be encapsulated to make it stable to passage through the gastrointestinal tract while at the same time allowing for passage across the blood brain barrier. See for example, WO 96/11698.

5 For parenteral administration, the compound may be dissolved in a pharmaceutical carrier and administered as either a solution or a suspension. Illustrative of suitable carriers are water, saline, dextrose solutions, fructose solutions, ethanol, or oils of animal, vegetable or synthetic origin. The carrier may also contain other ingredients, for example, preservatives, suspending agents, solubilizing agents, buffers and the like. When the compounds are being administered intrathecally, they may also
10 be dissolved in cerebrospinal fluid.

The conopeptides are administered in an amount sufficient to agonize the neuronal pacemaker calcium channels. The dosage range at which the conopeptides exhibit this agonistic effect can vary widely depending upon the particular condition being treated, the severity of the patient's condition, the patient, the specific conopeptide being administered, the route of administration and the presence of other underlying disease states within the patient. Typically, the conopeptides of the present invention exhibit their therapeutic effect at a dosage range from about 0.05 mg/kg to about 250 mg/kg, and preferably from about 0.1 mg/kg to about 100 mg/kg of the active ingredient. A suitable dose can be administered in multiple sub-doses per day. Typically, a dose or sub-dose may contain from about 0.1 mg to about 500 mg of the active ingredient per unit dosage form. A more preferred dosage will contain from about 0.5 mg to about 100 mg of active ingredient per unit dosage form. Dosages are generally initiated at lower levels and increased until desired effects are achieved.

EXAMPLES

25 The present invention is described by reference to the following Examples, which are offered by way of illustration and are not intended to limit the invention in any manner. Standard techniques well known in the art or the techniques specifically described below were utilized.

EXAMPLE 1

Experimental Procedures

30 Toxins and Bioassays. Venom of *Conus pennaceus* was obtained from specimens collected in the Northern Red Sea. Conotoxin-TxVIIA was from venom-purified aliquots (Fainzilber et al.,

1991). Assays for paralysis in limpet snails (*Patella caerulea*), bivalves (*Mytilus edulis*), and fish (*Gambusia affinis*) were performed as previously described (Fainzilber et al., 1995).

Column Chromatography. *Conus pennaceus* venom was extracted and fractionated on Sephadex G-50 (Pharmacia) and semipreparative C18 (Vydac) columns as previously described (Fainzilber et al., 1994). Final purification of the active peptides was on wide pore reverse-phase phenyl (Vydac, 25 x 0.46 cm, 0.5 μ m particle size) as described in Fig. 1, with on-line spectral analysis of peak purity utilizing a Hewlett-Packard 1040A Diode Array Detector coupled with HP 300 Chemstation Software.

Amino Acid Analysis. Analysis of amino acid composition after acid hydrolysis and 9-fluorenylmethyl-oxycarbonyl-chloride (Fmoc) derivatization was performed on a Merck-Hitachi reverse-phase HPLC system, according to Betner & Foldi, 1988. The system was calibrated prior to each analysis with Fmoc-amino acid standards.

Reduction and alkylation. Dried purified peptides were dissolved in 50 μ l of 0.1M NH_4HCO_3 (pH 8) containing 6M guanidine-HCl and 10 μ M EDTA, and reduced with 200 μ g of D11 at 37°C for 2 hrs under argon. 4-vinylpyridine, or iodoacetic acid, or iodoacetamide were added and the mixture incubated at 37°C for 1.5 hrs under argon. The alkylated peptide sample was purified on reverse-phase HPLC immediately after derivatization.

Edman Degradation Analyses. Reverse-phase purified peptides were applied to PVDF or glass fiber filters, and sequenced by automated Edman degradation on an Applied Biosystems 475A gas-phase protein sequencing system.

Proteolytic digest. HPLC purified sample of reduced and alkylated peptide was digested with TPCK-trypsin (Pierce, Rockford, IL) for 20 hrs at 37°C. A portion of the digest was directly analyzed by LC/ESI/MS, and the remainder purified by reverse-phase HPLC. pH of the digest was adjusted to 3.0 prior to loading on the HPLC, in order to minimize the possibility of γ -carboxyglutamate decomposition in extremely acidic conditions. Purified C-terminal peptide fragments were further digested by Endoproteinase Asp-N (Boehringer-Mannheim, Indianapolis, IN) for 20 hrs at 37°C, and immediately purified on reverse-phase HPLC. A portion of the purified Asp N peptide was then methylated for LSI CID mass spectrometry.

Mass spectrometry. Microbore LC/ESI/MS experiments were carried out on a VG/Fisons (Manchester, U.K.) platform mass spectrometer using a C18 column (macrosphere C18, 5 μ m particle size, 1 x 250 mm, Alltech, Deerfield IL) with a linear gradient of 2-62% acetonitrile in 0.1% TFA in 60 min. A post column addition of make up solvent, 2-propanol/2-methoxyethanol (1:1)

was used to optimize spraying and ionization performance (Medzihradszky et al., 1994). High energy CID mass spectra were obtained with a Kratos (Manchester, U.K.) Concept IIHH tandem mass spectrometer equipped with a continuous flow liquid secondary ionization source and a scanning charge-coupled device array detector (Burlingame, 1994).

5 Electrophysiology. Isolated *Lymnaea* caudodorsal neurons were kept in Petri dishes (Costar) and bathed in Hepes buffered saline (in mM: NaCl 30, NaCH₃SO₄ 10, NaHCO₃ 5, KCl 1.7, CaCl₂ 4, MgCl₂ 1.5, HEPES 10; pH 7.8 set with NaOH). To record calcium, sodium or potassium currents, HBS was replaced under continuous perfusion by the appropriate saline. The compositions of extracellular and pipette solutions used to selectively record specific currents were as follows (in
10 mM): Extracellular I_{Ca} saline: TEACl 40, CaCl₂ 4, HEPES 10, 4aminopyridine 2, pH 7.8 set with TEAOH; Extracellular I_{Na} saline: NaCl 47.5, CaCl₂ 4, MgCl₂ 1, HEPES 10, CdCl 0.1, 4-aminopyridine 1, pH 7.8 set with NaOH; Pipette saline (I_{Ca} and I_{Na}): CsCl 29, CaCl₂ 2.3, HEPES 10, EGTA 11, ATPMg 2, GTPtris 0.1, pH 7.4 adjusted with CsOH; Pipette saline (non-selective): KCl 29, CaCl₂ 2.3, HEPES 10, EGTA 11, ATPMg 2, GTPtris 0.1, pH 7.4 adjusted with KOH. Toxin was administered by means of a laboratory-built pressure ejection system through a small glass pipette (tip diameter 20 µM) placed at ~100 µM from the recorded cell. This enabled rapid application of toxins, which were applied continuously during voltage ramps or series of depolarizing voltage steps.

20 Membrane potential measurements were performed using sharp microelectrodes filled with 0.5 M KCl (40 MΩ) using an Axoclamp 2A (Axon Instr., Foster City, IA) amplifier in the bridge balance mode. Whole-cell voltage-clamp experiments were performed using the Axoclamp 2A amplifier in the continuous single electrode voltage clamp mode. Pipettes (2-6 MΩ) were pulled on a Flaming/Brown P-87 (Sutter Instruments, CO) horizontal micro-electrode puller from Clark GC-150T glass (Clark Electromedical Instruments, U.K.) (seal resistance >1 GΩ). After disruption
25 of the patch membrane series resistance (< 10 MΩ) was compensated for --80%. With current amplitudes of <5 nA, the maximal voltage error is estimated to be ≤10 mV. Cell capacitance (~ 100 pF) was not compensated. Measurements of calcium or sodium currents were commenced 20 mins after access to the cell, in order to allow equilibration with the pipette solution. Data acquisition was controlled by a CED AD/DA converter (Cambridge Electronics Design, Cambridge, U.K.)
30 connected to an Intel 80486-based computer, run with voltage-clamp software developed in our laboratory. The current recordings were filtered at 1-5 kHz, sampled at 1 kHz (calcium currents and

K⁺ currents) or 3 kHz (Na⁺ currents) and stored on-line. This system allowed simultaneous application of voltage-steps, acquisition of current recordings and timed application of toxins.

EXAMPLE 2

Purification of γ -Conotoxin PnVIIA

Conus pennaceus venom was fractionated as described under Methods, and reverse-phase peptide containing fractions were assayed for γ Glu content using a comparison of positive ion versus negative ion modes of MALDI mass spectrometry (Nakamura et al., 1996). The positive fraction indicated as PnVII in Fig. 1B of Fainzilber et al. (1994) was repurified by reverse phase phenyl chromatography and conotoxin-PnVIIA was obtained as the major component. On-line spectral analyses of the final chromatographic step suggested homogeneity of the purified toxin. ESI/MS measurements of the purified peptide revealed a single mass of 3718.4, further confirming homogeneity of PnVIIA.

EXAMPLE 3

Chemical Characterization of γ -Conotoxin PnVIIA

Automated Edman sequencing of PnVIIA after alkylation with 4-vinylpyridine revealed a 32 amino acid sequence, allowing unambiguous assignments of 30 residues (Table 2). The extremely low yields of Glu at steps 14 and 26 further suggested the presence of γ -carboxyglutamate residues at these positions. Amino acid composition analysis (Table 3) was consistent with the proposed sequence (Table 4), and the ESI/MS measurement fits that predicted from the sequence assuming two γ -carboxyglutamate residues, three disulfide bridges and a free carboxy terminus (measured mass 3718.4, predicted 3719.0).

TABLE 2

Edman Degradation of PnVIIA

	<u>Cycle #</u>	<u>Assigned Residue</u>	<u>Yield (pmoles)</u>
5	1	Asp	185
	2	Cys	170
	3	Thr	180
	4	Ser	190
	5	Trp	170
10	6	Phe	140
	7	Gly	210
	8	Arg	85
	9	Cys	93
	10	Thr	150
15	11	Val	170
	12	Asn	85
	13	Ser	110
	14	Glu	9
	15	Cys	50
	16	Cys	56
	17	Ser	18
	18	Asn	35
	19	Ser	15
	20	Cys	11
	21	Asp	23
	22	Gln	26
	23	Thr	22
	24	Tyr	17
	25	Cys	14
30	26	Glu	3
	27	Leu	17
	28	Tyr	14
	29	Ala	11
	30	Phe	13
35	31	Hyp	8
	32	Ser	9

TABLE 3

Amino Acid Composition Analysis of Conotoxin-PnVIIA

<u>Amino Acid</u>	<u>Mole Ratio</u>
Asx	3.9 (4)
Ser	4.7 (5)
Glx	3.0 (3)
Cys	5.2 (6)
Thr	2.8 (3)
Gly	1.1(1)
Arg	1.0 (1)
Hyp	0.8 (1)
Ala	1.2 (1)
Tyr	2.0 (2)
Val	1.2 (1)
Phe	2.0 (2)
Leu	1.2 (1)
Trp	n.d (1)

Molar ratios of amino acids determined after acid hydrolysis and FMOC derivatization. Values in brackets are those predicted from the amino acid sequence.

TABLE 4

Amino Acid Sequence of PnVIIA and TxVIIA

PnVIIA (SEQ ID NO:42): D C TSWFGR C T V N SvCCS N S C DQT YC Y L YAFOS-COOH
 TxVIIA (SEQ ID NO:43): C GGYSTY C Y V D SvCCS D N C VRS YC T L F-NH₂

Sequence identities are underlined; similarities are in bold type; and spaces inserted to maximize homologies.

In order to verify the presence of γ carboxyglutamate, and to determine the C-terminus, the peptide was further analyzed by mass spectrometry. A tryptic digest of reduced and carboxymethylated PnVIIA gave two peptides, T1 and T2, whose average molecular masses by ESI/MS were 1029.0 and 3062.6, respectively. These masses fit those predicted for the two PnVIIA tryptic peptides, namely 1029.1 for the sequence DXTSWFGR (SEQ ID NO:44), where X is carboxymethylCys, and 3062.2 for the sequence XTVNSX₁XXSNSXDQTYXX₁LYAFX₂S (SEQ ID NO:45), where X₁ is γ -carboxyglutamate and X₂ is 4-trans-hydroxyproline. Asp-N digest of the C-terminal tryptic peptide T2 gave two products, AN1 and AN2. ESI/MS average mass for AN1 was 1525.4, fitting the predicted mass of the Asp-N fragment XTVNSX₁XXSNSX (residues 1-12 of SEQ ID NO:45; predicted 1525.6). The monoisotopic LSI/MS measured mass for the C-terminal

fragment AN2 was 1553.7, in agreement with the calculated value assuming the C-terminal is a free acid. An attempt to further confirm the C-terminal sequence of PnVIIA by LSI tandem MS failed, perhaps due to poor ionization efficiency of AN2. Therefore, PnVIIA was reduced and alkylated with iodoacetamide, a procedure expected to generate derivatives with better CID spectra than carboxymethylated peptides. After trypsin followed by Asp-N digests, the C-terminal carbamolmethylated peptide AN2u was isolated. Methylation with HCl/MeOH gave a tetra ester, with monoisotopic LSI/MS mass of 1608.9. This mass fits a peptide with incorporation of four methyl groups -- one at the side chain of Asp, two at the carboxyl groups of the γ -carboxyglutamate, and the fourth at the presumed C-terminal free carboxyl (predicted monoisotopic mass 1608.7). The protonated tetra-methylated AN2u was further analyzed by CID mass spectrometry, giving a spectrum confining all details of the C-terminal sequence. The γ -carboxyglutamate residue is clearly indicated by the immonium ion at m/z 174, and its position revealed by the b5 and b6 molecular ions. The y2 ion confirms a C-terminal structure of -Hyp-Ser-OMe, derived from the free carboxy terminal of PnVIIA. Thus, the sequence of the peptide including the modified residues γ -carboxyglutamate and Hyp was confirmed; and the free carboxy terminus established by mass spectrometry.

PnVIIA belongs to the large group of conotoxins with the cysteine framework of ω and δ conotoxins, however, the sequence is most homologous to conotoxin-TxVIIA (Table 4). These homologies comprise approximately 48% amino acid identity and 63% similarity, including positioning of most hydrophobic and some charged residues, as well as one of the γ -carboxyglutamates.

EXAMPLE 4

Biological Activity of γ -Conotoxin PnVIIA

Paralytic Activity of PnVIIA. Initial injections of PnVIIA to limpet snails (*Patella*) did not reveal the contractile paralysis previously observed for TxVIIA and other conotoxins in this bioassay (Fainzilber et al., 1991), however at doses above 50 pmoles/100 mg body weight some flaccidity of the foot musculature could be observed. Flaccid or relaxation paralytic effects are more easily observed in bioassays on bivalve molluscs, hence toxicity of PnVIIA was quantified in bioassays in freshwater mussels (*Mytilus*), as previously done for conotoxins PnIVA and PnIVB (Fainzilber et al., 1995). The ED_{50} for *Mytilus* paralysis was 63.2 pmoles/100 mg body weight. No toxic or other effects could be observed upon injection of 1 nmole PnVEA (15-fold higher than the

Mytilus ED₅₀) per 100 mg body weight in *Gambusia* fish or blowfly (*Sarcophaga*) larvae. Interestingly, decarboxylated PnVIIA had no observable effects on *Mytilus* at doses of up to five-fold the ED₅₀ of the native peptide.

Electrophysiological Effects of PnVIIA on *Lymnaea* Neuroendocrine Cells. Effects of PnVIIA were first screened in a number of mollusc or vertebrate electrophysiological preparations. Consistent effects were observed on caudodorsal neurons from the snail *Lymnaea stagnalis*, and this system was therefore used for detailed investigations on toxin activity. The caudodorsal neurons are typical rhythmic bursting cells responsible for production of egg laying hormone, and their ionic currents have been characterized exhaustively (Brussaard et al., 1991; Dreijer & Kits, 1995; Kits & Mansvelder, 1996). In the first series of experiments, PnVIIA was applied to caudodorsal neurons recorded under current clamp and the effects on membrane potential and action potential firing were investigated. It was found that PnVIIA enhances the excitability of these cells in a dose-dependent way. Thus, a dose-dependent increase in excitability of caudodorsal cells (CDCs), inducing depolarization and repetitive spiking upon application of micromolar doses of PnVIIA was seen. Cells that were silent responded to low doses ($\leq 1 \mu\text{M}$) of the toxin by depolarization, while doses of $10 \mu\text{M}$ or more induced trains of action potentials. The number of action potentials increased with increasing doses. The duration of PnVIIA application also markedly influenced the response. In silent cells, responding with a burst of action potentials, the number of action potentials and the duration of the burst increased with increasing duration of the PnVIIA pulse. Thus, a time dependence of the excitatory effect of PnVIIA in silent CDCs, showing increased duration of spiking with increased duration of application was seen. Cells that were spontaneously active responded by a temporary increase in firing frequency, followed by an afterburst hyperpolarization during which the cell stops firing for a short period. Increasing the duration of PnVIIA application under these circumstances led to an increase in the duration of the burst, but even more so in the duration of the afterburst silent refractory period. Thus, a time dependence of the excitatory effect of PnVIIA in spontaneously active CDCs, showing that not only spiking increases but also the duration of silent period after the afterburst increases with longer applications was seen. The latter effect is possibly indirect, as a natural consequence from the increased firing frequency induced by the toxin.

Whether the effect was due to closure (blockade) or opening (activation) of ion channels was investigated by measuring input resistance of the cell membrane upon injection of hyperpolarizing current pulses ($30 \mu\text{A}$). The amplitude of the resulting hyperpolarization is a direct measure of the

membrane resistance. In this experiment, pulses of hyperpolarizing current were injected into CDCs, giving rise to hyperpolarizations of the membrane potential. While the injected current is constant, the hyperpolarizing response decreases upon application of PnVIIA, showing that the membrane resistance decreases or, in other words, the membrane conductance increases. It was seen that during PnVIIA application hyperpolarization amplitude is strongly decreased (~ 50% attenuation), thus revealing a marked decrease in membrane resistance. Thus, PnVIIA induces an increase in conduction, i.e., leads to the opening of ion channels, and therefore acts primarily as a channel agonist or activator, rather than as a channel blocker.

In a further series of experiments, the identity of the channel(s) activated by PnVIIA was investigated. To this end, whole cell voltage clamp experiments were performed on caudodorsal neurons, however, no consistent effects of the toxin could be observed on fast voltage gated sodium or calcium currents, nor on the potassium currents that are activated in a standard voltage step protocol. A slow ramp protocol was then applied to investigate possible effects on slow voltage gated currents (also designated as pacemaker currents) that are believed to underlie spontaneous firing. In this experiment current responses to a voltage ramp protocol in standard HBS during which the membrane potentials go from -80 to +20 mV at a rate of mV/s (control) were measured. This protocol will only reveal slow, voltage-gated currents, as fast currents will inactivate during the slow voltage ramp. An inward current is activated at ~ -30 mV and more positive. Most likely, this represents a pacemaker current. With 10 μ M PnVIIA (10 μ M) the voltage dependence shifts to the left (i.e., the current activates already at more hyperpolarized potentials). Furthermore, an increase in outward current at $> \sim 0$ mV occurs. Thus, the experiments indicated that a noninactivating inward current is activated at voltages above ~ 30 mV to the voltage ramp protocol. Preliminary experiments indicate that this inward current is a nonspecific cation current that is reduced in Na^+ free selective saline and completely blocked by 1 mM Ni^{2+} . Thus, most likely, Na^+ and Ca^{2+} carry the inward current. In voltage dependence and ion selectivity, this current strongly resembles a pacemaker current in other *Lymnaea* neurons elaborately described by van Soest and Kits (1997). In the presence of 10 μ M PnVIIA, a dual effect was observed. First, the activation range of the slow inward current shifted by ~ 10 mV to a more negative potential, thus accounting for the enhanced excitability of the cells. Second, we saw an increase in noninactivating outward current at potentials above ~ 0 mV. Whether the latter is a direct effect of PnVIIA, or an indirect effect due to the increased inward current, remains to be determined. It is, however, in line with the previously observed prolongation of afterburst hyperpolarization under current clamp conditions. These data

show that the primary event mediating the excitatory effects of PnVIIA on *Lymnaea* caudodorsal neurons is an enhancement of a slow, voltage-activated inward cation channel.

EXAMPLE 5

Isolation of a γ -Conotoxin Tx6.4 from *Conus textile*

A *Conus textile* cDNA library was prepared from venom duct using conventional techniques. DNA from single clones was amplified by conventional techniques using primers which correspond approximately to the M13 universal priming site and the M13 reverse universal priming site. The primers which were used are:

5'-TTTCCCAGTCACGACGTT-3' (SEQ ID NO:46) and

5'-CACACAGGAAACAGCTATG-3' (SEQ ID NO:47).

Clones having a size of approximately 300 nucleotides were sequenced and screened for similarity in sequence to PnVIIA and TxVIIA. A DNA was isolated having the sequence set forth in SEQ ID NO:16, which encoded the propeptide sequence set forth in SEQ ID NO:17. This new γ -conotoxin has the sequence described above and set forth in SEQ ID NO:7. Preferably, Xaa₁ is Trp, Xaa₂ is γ -Glu and Xaa₃ is Hyp. The C-terminus preferably contains a free hydroxyl group.

EXAMPLE 6

Isolation of γ -Conopeptides

The procedure of Example 5 was followed to isolate additional nucleic acids encoding γ -conopeptides. The nucleic acids which were isolated have the nucleotide sequences set forth in SEQ ID NOs:18, 20, 22, 24, 26, 28, 30, 32 and 34. These nucleic acids encode the propeptides having the amino acid sequences set forth in SEQ ID NOs:19, 21, 23, 25, 27, 29, 31, 33 and 35, respectively. The mature peptide sequences are set forth in SEQ ID NOs:8-15 and 36.

EXAMPLE 7

Biological Activity of γ -Conotoxin TxVIIA

Isolated medial neurons from *Aplysia oculifera* pleuropedal ganglia (Kehoe, 1972) were cultured as previously described (Schacher & Proshansky, 1983). The neurons were cultured at very low densities to prevent any possible synaptic interactions among them. Passive and active membrane properties of the cultured neurons were studied using conventional intracellular recording and stimulation techniques. Briefly, the cell body of a cultured neuron was impaled by two

microelectrodes filled with 2 M KCl (5-10 M Ω resistance), one for current injection and the other for voltage recording. Analysis of the resting potential, input resistance, and action potential amplitude and shape was carried out in artificial sea water composed of 460 nM NaCl, 10 mM KCl, 11 mM CaCl₂, 55 mM MgCl₂ and 10 mM Hepes, pH 7.6. Venom fractions for electrophysiological experiments were dissolved in artificial sea water containing 10 mg/ml bovine serum albumin. The Sephadex™ G-50 fraction was applied at 100-200 μ g/ml and purified toxin at final concentrations of 0.25-0.5 μ M.

The effects of venom fractions and purified toxin on isolated *Aplysia* neurons were characterized by measuring the resting potential, input resistance and action potential amplitude and shape. The Vt fraction from the Sephadex™ G-50 column (G-50-Vt) (Fainzilber et al., 1991) and the purified toxin revealed significant effects at concentrations of 100 μ g/ml and 0.25-0.5 μ M, respectively. The effects of G-50-Vt, TxIA and TxIB were essentially similar (Fainzilber et al., 1991). These fractions induced a transient membrane depolarization of 5-12 mV for 40-120 s. Within 3-30 s. after bath application of the toxin, the quiescent neurons fired spontaneously. Concomitantly, the action potential duration increased by one to two orders of magnitude, extending in many experiments to over 1 s. The prolonged action potentials are typically composed of an initial spike with a prolonged shoulder. In the continuous presence of the toxin in the bathing solution, the action potential duration gradually recovers. 20-30 min. after toxin application, the action potential duration was only 50-100% longer than in the control. Throughout this period, the threshold for action potential initiation was reduced. The changes in membrane excitability and action potential duration induced by the toxins were completely reversible upon washing of the neuron with artificial sea water. TxI-induced prolongation of the action potential duration was observed also when Ca²⁺ and K⁺ conductances were blocked (Ca²⁺ free artificial sea water, 16 mM Ca²⁺ and 50 mM tetraethylammonium, 150 μ M 3,4-diaminopyridine and 10 nM Cs⁺). Addition of tetrodotoxin (10 μ M) under these conditions reduced the TxI-induced spike prolongation. TxVIIA induced similar effects on the membrane properties of isolated neurons, including membrane depolarization and repetitive firing. However, TxVIIA did not cause any increase in action potential duration.

The amino acid sequence of PnVIIA conserves the six-cysteine, four-loop framework C...C...CC...C...C typical of ω and δ conotoxins, and as shown in Table 4, is most homologous to the sequence of conotoxin-TxVIIA, an excitatory toxin from *Conus textile* venom (Fainzilber et al., 1991; Nakamura et al., 1996). Both of these toxins have an identical, extremely acidic net charge (-5) and

are similar in their surface hydrophobic/hydrophilic interaction properties, as evidenced by comparable elution properties in reverse-phase chromatography. Furthermore, the grow effects of these toxins in their respective sensitive systems (*Aplysia* versus *Lymnaea* neurons) are very similar, comprising an enhancement of excitability decreased membrane resistance, and increased repetitive firing. PnVIIA and TxVIIA may therefore represent closely related members of the same family, or convergent evolution to closely related receptor/channel targets.

The paralytic activities of both TxVIIA and PnVIIA in their respective bioassays are markedly decreased upon decarboxylation of the γ Glu residues. Although the primarily structural importance of γ Glu-metal chelates in mammalian vitamin K-dependent blood coagulation proteins and in mollusc conantokins is well established (Freedman et al., 1995; Skjaerbaek et al., 1997), there is also evidence, for example, in prothrombin of a functional role of individual γ Glu residues in membrane binding (Ratcliffe et al., 1993). Although the 3-D structures of conotoxins TxVIIA and γ PnVIIA are most likely directed and stabilized by the three disulfide bonds, as in conotoxins in general, we cannot rule out at this stage a secondary microstructural role of the γ Glu residues. However, an attractive hypothesis is that the γ Glu residues in these peptides form part of a membrane or receptor recognition patch, with other variable residues (Table 4) providing specific recognition for channel isoforms or subtypes. Hypervariability in structurally related conotoxins is a well established mediator of the exquisite selectivity of these peptides for receptor subtypes (Myers et al., 1993; Nielsen et al., 1996).

It will be appreciated that the methods and compositions of the instant invention can be incorporated in the form of a variety of embodiments, only a few of which are disclosed herein. It will be apparent to the artisan that other embodiments exist and do not depart from the spirit of the invention. Thus, the described embodiments are illustrative and should not be construed as restrictive.

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- PCT Published Application WO 96/11698

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